Chapter 9
System Shutdown and Confirmation of Cleanup

9-1. Introduction

The attainment of agreed-upon conditions under which remediation activities may cease and the SVE/BV system may be decommissioned is the ultimate objective of the remediation effort. This requires a series of steps to demonstrate that the air being processed and the soil in the treatment area have met established criteria.

9-2. Shutdown Strategy

a. Federal and state regulatory media-specific cleanup requirements, voluntary cleanup requirements, or risk-based requirements established for the particular contaminant(s) to be remediated drive the shutdown of a remediation system. Site-specific cleanup objectives are usually established by the Federal and/or state agencies, if no generic cleanup levels exist. In many cases, the cleanup requirements are determined based on a need to protect the quality of the underlying ground water. As the initial step in determining the shutdown strategy, the design team must be familiar with all Federal and/or state soil cleanup objectives. Table 9-1 lists factors that may influence one to commence shutdown.

Table 9-1
Possible Criteria to be Considered in Evaluating Shutdown of SVE/BV System

Offgas Analysis (Continuous and Pulse Venting - ***MUST be considered in conjunction with other data***)
• Total emissions or individual VOCs exiting blower exhaust are not evident.
• Total emissions or individual VOCs exiting blower exhaust reach predetermined levels.
• Total emissions or individual VOCs exiting blower exhaust reach asymptotic conditions and design deemed adequate.
• No rebound is observed in influent concentrations upon system restart, following reasonable system shutdown period.
• Operation costs greatly exceed value of continued vapor removal (operator's decision).
• Pulse venting down time greatly exceeds pulse venting operation time (operator's decision).
Bioventing Respiration
• Oxygen respiration measurements performed within the area being remediated indicate declining contaminant degradability, relative to a background control.
Soil Gas Analysis (from monitoring probes) ***Recommended***
• Soil gas constituents collected from remediation area reach asymptotic conditions and extraction and monitoring system designs deemed adequate.
• Soil gas constituents collected from the remediation area indicate levels of nondetection with reasonable detection limits and concentrations.
• Soil gas constituents collected from the remediation area indicate levels of residual mass that is no longer threat to ground water
• Soil gas concentrations do not significantly rebound following reasonable system shutdown period

Table 9-1
Possible Criteria to be Considered in Evaluating Shutdown of SVE/BV System

Soil Sample Analysis ***Recommended, provided proper sampling strategy and methods used***
• Soil constituents collected from the area being remediated indicated levels below regulatory requirements or levels of nondetection (confirmatory analyses).
• If soil constituents collected from the area being remediated indicate levels above regulatory requirements, and operation times and cost have been exceeded, the operator may request a variance from the regulatory agency to accept remediated levels (refer to paragraph 9-5, Evaluation of Results).

b. Shutdown strategies can be based on:

- Soil sampling results compared to specific regulatory or risk-based soil concentration standards
- Soil gas sampling, compared to specific soil gas concentration standards
- Soil gas concentration rebound following shutdown for reasonable period (see Section 9-9 and Appendix F)
- For BV systems, attainment of low respiration rates

In all cases, the design of both the remediation and the monitoring system must be evaluated to ensure it is in accordance with good practice, as defined by this manual.

c. Shutdown strategies based on the need to protect ground water are becoming more common. In most cases, the removal of contaminant mass in the vadose zone must continue until the residual mass will not leach to the ground water in quantities that would cause exceedance of ground water quality standards. This typically is evaluated through the use of leaching models and the assumption that some mixing of the leachate and ground water occurs below the water table. The details of this mixing (i.e., thickness of mixing zone, etc.) are often the subject of debate. It is unrealistic to neglect this mixing, but it is not conservative to overestimate the thickness of the mixing zone in the absence of hydrogeologic data. The observed thickness of the ground water plume or the typical length of either monitoring well screens or production well screens may be a basis for the thickness of the mixing zone. The acceptable soil concentration may be determined through the modeling (DiGiulio et al., 1999), or, by assuming equilibrium between phases, an acceptable soil gas concentration can also be computed. At an Air Force Base in California, further analysis has been done to determine the acceptable soil remediation by SVE considering the cost of simultaneous ground water extraction. The evaluation considers the cost of removing additional mass through the SVE system, versus the additional cost for future ground water extraction accounting for the added leachate from the vadose zone if SVE is stopped. The operation of the SVE system would continue only if the reduction in the cost of future ground water extraction was more than the cost of the additional SVE. This requires the use of both vadose zone leaching and ground water contaminant transport models and is probably justified only on larger SVE sites where ground water is already impacted.

d. The USACE Remediation System Evaluation process can also be used to help identify when the system may be ready for shutdown or when enhancements may be necessary to reach remediation goals. Refer to the Soil Vapor Extraction Subsurface Performance checklist available at http://www.environmental.usace.army.mil/library/guide/rsechk/rsechk.html. The checklist guides the user in analysis of data to determine if the system has reached a limitation, if operation needs to be changed to improve progress toward closure, if a change or addition of remediation technologies is warranted, or if the system can be closed.

9-3. Sampling and Analysis

a. To verify that cleanup criteria have been achieved, the sampling plan described in the SAP will be carried out. The sampling is likely to be more exhaustive both spatially and analytically than that used during routine monitoring. The DQOs will probably be more rigorous as at this stage the consequences of errors are more serious. It will be important when determining cleanup confirmation or compliance with ARARs to use sampling techniques that are consistent with those used at system start-up, so that comparisons between the two sets of data are meaningful. Quality Assurance/Quality Control (QA/QC) samples, such as field duplicates, equipment blanks, trip blanks, and split samples sent to the USACE QA laboratory, will be an important component of the sampling program. Adherence to standard operating procedures, including sample notation and chain-of-custody procedures, is critical at this juncture. Table 3-4 lists the topics covered in a SAP.

b. It is important to note that it is NOT appropriate to wait until sampling for "closure" to perform thorough sampling and analysis of key soil venting parameters. In order to operate the system optimally, it is critical to frequently monitor parameters such as extracted concentration and flows from individual wells, in-situ soil gas concentrations from vadose zone piezometers, and water table fluctuations. A more comprehensive list of routine sampling parameters is found in Chapters 7 and 8. In addition the RSE checklists describe a set of parameters that should be monitored periodically to ensure that the system is operating as intended. By maintaining a good database of the "routine" operational data, the practitioner is unlikely to be surprised by the results of the sampling and analyses described in this chapter.

c. *Analytical.* Definitive fixed-laboratory analyses are usually required at this stage. Use of standard analytical methods and reference materials to enhance comparability of data over time and across laboratories will make the comparison valid. An example of a reference material might be a sample of floating product from a monitoring well in the case of remediation of a gasoline release. An aliquot of this product would be analyzed every time a set of field samples was analyzed to indicate differences in analytical response. Completion of remediation will be documented by attainment of agreed-upon contaminant concentrations using agreed-upon sampling and analysis methodologies.

9-4. Typical Data Trends

Usually the most concentrated exhaust stream treated by an SVE system is encountered at the beginning of remediation. The typical data trend for vapor phase contaminant concentrations is steeply downward for two to three months, after which concentrations approach asymptotic levels. This is graphically depicted for six example sites in Figure 9-1. Some systems are operated intermittently (pulsed) to periodically permit the soil system to equilibrate and introduce additional VOC into the soil air to maximize vapor phase concentrations. This may make the air treatment system more efficient, particularly for catalytic combustion treatment systems (see paragraph 8-2).

a. If the data do not demonstrate an appreciable reduction in vapor phase contaminant concentrations over the first few months of operation, it is possible that NAPL is present and acting as a continuing source of VOC vapors.

b. Several data trends are commonly encountered in monitoring contaminant concentrations in soil, soil gas, and vent gas. Residual soil contamination (paragraph 2-3c(6)) decreases with venting time, and distillation effects are apparent from preferential evaporation of more volatile compounds, leaving heavier compounds behind. However, tracking residual contamination accurately requires analyzing a large number of samples because soil, being an unmixed medium, is heterogeneous. Analysis of residual contamination is usually limited to before venting, to determine starting concentrations, and after the venting operation is complete, to confirm that treatment goals have been met. (Analyses of residual contamination in soil samples are actually analyses of the residual plus aqueous plus vapor phase contaminants.)

c. SVE shutdown should not be considered in isolation at sites with underlying contaminated ground water. Concentrations of contaminants in ground water should also be monitored to determine the contribution of contaminants from the aqueous phase to the soil gas. A site contaminated with up to 55 mg/kg of PCE in soil was subjected to SVE to achieve a cleanup goal of 1 mg/kg. After 9 months, the PCE concentration in vent gas was less that 1 percent of its initial value. Soil gas concentrations met shutdown criteria, but soil sample analyses showed PCE concentrations of up to 15 mg/kg. It was found that groundwater was recontaminating the soil by capillary action and water table fluctuations. Bulk fluid movement during a period when the water table rose and fell evidently accelerated the mass transfer process from the saturated zone to the unsaturated zone. Solute was apparently transported up into the vadose zone during a water table rise, and then exposed to soil gas in the vadose zone following a drop in the water table and draining of soil near the capillary fringe. Under stagnant water table conditions, by contrast, the mass transfer process would tend to be diffusion limited and therefore four orders of magnitude slower than during a period of bulk fluid movement. A rough calculation showed that groundwater could have contributed 270 kg of the more than 325 kg of PCE that were removed by the SVE system (Urban 1992). By performing extensive simulations using the multi-phase flow model, T2VOC, Williams et al. (2000) have demonstrated a similar phenomenon at the Twin Cities Army Ammunitions Plant (TCAAP).

d. Air, being a mixed medium, is more economical than soil for monitoring the progress of SVE/BV operations. Vent gas concentrations can provide a gauge of mass removal from the whole soil volume affected by the SVE/BV system, while soil gas monitoring can resolve spatial variation in vapor phase contaminant concentrations. Monitoring of vapor phase compounds, including both VOCs and O_2, CO_2 and methane in monitoring points will assist greatly in calibrating flow models and improving confidence in the results of the modeling. Another parameter which may be measured is tracer gas concentration at monitoring points after injection of the gas into a specified point. This permits estimation of flow velocities to assist in calibration of models and estimation of pore volume exchange rates across the site (USEPA, 1996).

e. BV is at times employed for treatment of soils contaminated with weathered fuels containing relatively heavy petroleum hydrocarbons. In such applications, soil concentrations have been observed to decline moderately fast at first, then the degradation rates decline slowly over time. Concurrent shutdown testing performed periodically indicated that oxygen uptake rates declined over time, signaling that most of the more biodegradable constituents had been consumed. A risk-based approach to viewing such data might argue that if the remaining constituents are so low in solubility and volatility that they are no longer bioavailable under operating conditions that are known to favor biological activity, they may no longer present a risk, provided that direct contact exposure routes can be prevented through appropriate administrative or containment measures (Smith et al. 1995).

f. Hiller (1991) reviewed a number of full-scale SVE case histories and selected for analysis six well-documented successfully vented sites with TCE and/or PCE contamination which varied somewhat in geologic setting and initial contaminant concentrations. Vent gas PCE/TCE concentrations followed similar trends at the six sites, with an initial steep 80 to 90 percent decline lasting about 20 days, followed by a gradual asymptotic decrease to background concentrations. During this latter phase, concentrations were similar among sites, falling from 20 ppm or less to about 2 ppm in the final stages after 6 months. The data are shown in Figure 9-1. This was interpreted to reflect initial rapid evaporation of free product droplets, followed by a diffusion-controlled process of partitioning of contaminants previously dissolved in soil moisture into the gaseous phase and desorption from soil particles. However, sharp declines in extracted vapor concentrations do not always indicate that advective removal has ended. If only aggregate vapor concentrations are monitored (i.e., from a common header), then the behavior of each well is masked. Areas that contain high concentrations, but yield low air flowrates may be obscured by wells that yield higher flow rates. This emphasizes the importance of monitoring individual wells.

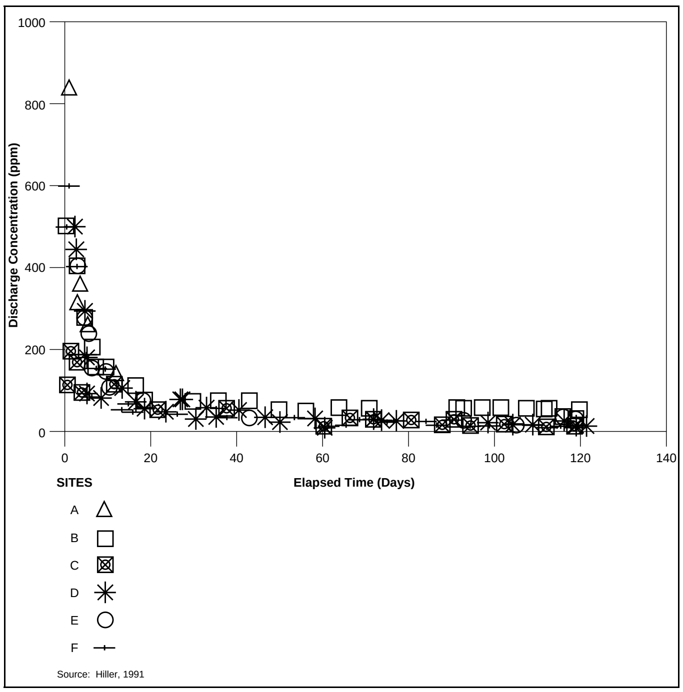

Figure 9-1 Vent Gas VOC Concentrations at Six Sites Over Time

9-5. Evaluation of Results

a. Methods of evaluation for shutdown. The results of the sampling and analyses described above must be carefully evaluated before deciding that the system is ready to be shut down. Typically, the criteria for determining when the system can be shut down include one or more of the following:

- Total amount of contaminant removed.
- Residual soil concentrations.
- Extraction well(s) vapor concentrations and composition.
- Soil gas contaminant concentrations and composition in monitoring points.

b. Mass Removed. Given the often highly uncertain quantity of material released or mass present in the subsurface prior to remediation, the comparison of the mass removed to the mass initially present is a poor criteria for shutdown. At some sites, such as a Superfund site in Arizona, more mass was removed in the pilot test than was estimated during the remedial investigation to be present at the entire site, and mass removal was still high at the end of the test.

c. Target soil concentrations. As discussed above, many states' target cleanup levels, especially for petroleum hydrocarbons, ultimately limit the residual concentrations of contaminants in the soil. Since soil sampling is both costly and potentially disruptive, the site operator will want to be quite certain that the soil samples will show that the cleanup levels have been attained before they are collected. For this reason, the shutdown sampling is typically conducted in stages, whereby the attainment of one criterion will trigger the next level of testing, and so on, until achievement of cleanup levels is confirmed. For example, the first criterion might be the attainment of a target vapor concentration in monitoring points, based on a correlation between extracted vapor and soil concentrations. If this target were met, the system might be shut down for a number of days, after which the in-situ soil gas concentrations and composition would be analyzed. If the soil gas results following shut down met target levels, only then would actual soil samples be collected. Finally, the results of the soil analyses would be compared with the actual cleanup levels for residual soils. At this point, the system might be shut down, but often the equipment will remain in place for some period of time in the event that future confirmatory samples show that concentrations have risen above cleanup levels again, in which case system operation would be resumed. The use of soil sampling for confirmation of cleanup and system shutdown must consider carefully the heterogeneous distribution of soil concentrations at a site and the uncertainties associated with sampling soils for VOCs. Soil sampling to confirm cleanup requires the use of statistically based sampling strategies to quantify the certainty of achieving goals (USEPA, 1989e). The current SW-846 method 5035 is strongly recommended for sampling soils for VOCs.

d. Extracted Vapor Concentrations and Composition.

(1) In many cases, the SVE system is operated until the concentrations in the extracted vapors either drop to non-detectable levels or to some asymptotic (but low) level. There are some caveats to this method, however. First, although the decrease of concentrations in the <u>extracted</u> vapor is an indication of the effectiveness of the system, it is certainly not conclusive evidence that the concentrations in the soil have decreased proportionally. Johnson, Kemblowski, and Colthart (1990b) list other potential reasons for decreases in vapor concentrations:

- Water table upwelling.
- Soil drying.
- Diffusion constraints.
- Short-circuiting.

Use of the concentrations in the influent or from an individual extraction well for shutdown decisions, in the absence of other data, is also prone to errors due to the large component of relatively clean flow to many extraction wells that often enters the subsurface near the well. This large component of the flow travels through the zones near the well that are thoroughly flushed after some operation compared to soils at greater distances from the vent. It is quite easy to design an SVE system that reaches low influent concentrations while still leaving a significant quantity of mass in the soils, especially near stagnation zones. Because of this uncertainty, the composition of the extracted vapors is usually monitored as well as the concentrations.

(2) Holbrook et al. (1998) explain that if the composition of the extracted gas stream from an SVE system at a petroleum fuel site reflects higher and higher boiling compounds, then the extraction system can be considered to have successfully remediated the site relative to the more volatile compounds. The system may then be focussed on bioventing the less volatile components. This approach is applicable to sites where the SVE system is affecting all of the contaminated soil. If there are pockets of contamination that are subject to rate-limited mass transfer and are not being remediated by advective flow, or are only slowly being remediated, then changes in extracted gas composition will NOT allow evaluation of how close the system is to achieving specific cleanup goals. Rather, compositional analysis provides insight into how well the system is performing relative to its ability to treat the part of the problem it can "reach" advectively.

e. Rebound of concentrations in extracted vapors. An alternate method of applying this approach involves the use of pulse extraction, where an area is alternately subjected to a vacuum and then allowed to return to “atmospheric” conditions. This method may be employed by using the same vacuum pump to treat two (or more) areas of a site, and cycling over two-week (or other) operating pulse times. When an area is brought back under vacuum, the initial concentrations of VOC are measured in the extracted airstream and compared with the initial readings for previous operating cycles. The initial concentrations at each cycle are plotted versus time to demonstrate a drop in the “equilibrium” soil air concentrations. An example of this graph is shown in Figure 9-1. When the initial cycle concentration approaches zero for the compounds of concern, consideration should be given to entering the shutdown phase. Further information regarding rebound testing is provided in section 9-9 and Appendix F. The use of rebound testing based only on extracted vapors is subject to the same uncertainties and caveats discussed above.

f. Soil gas concentrations in monitoring points. Soil gas concentration and composition in strategically placed monitoring probes can be the most effective indicators of the progress toward cleanup. As stated in Chapter 5, monitoring points must be installed in areas that will be the most difficult to remediate and placed in geologically representative strata. If soil gas concentrations decline in areas between extraction (and injection) wells where air throughput or oxygen delivery is the least effective, then the system is probably being effective. Soil gas concentrations are less expensive to collect, and generally represent more integrated (i.e., from a larger area) data. Adequate purging must be conducted before sampling, however. Although soil gas sampling conducted during remediation is often done, care must be taken to not allow clean air entry into the monitoring probe before purging since the subsurface is usually under vacuum relative to the atmosphere. Sampling conducted during remediation also represents the dynamic condition where clean air is being drawn into the treatment areas, and the diffusion-driven release of contaminant vapors is diluted by the entry of clean air. Soil gas sampling of monitoring points following temporary shutdown is a more reliable means to assess progress. Some rebound of soil gas concentrations in monitoring points is likely following shutdown and rebound may take weeks. When significant rebound is not observed, available mass has probably been removed. Remaining mass is likely in low-permeability zones that are unlikely to allow significant leaching of mass to occur. If regulatory requirements permit, soil gas concentrations from monitoring points are the preferred data to use for establishing clean closure.

g. For BV systems, the focus of evaluation of treatment progress should be on contaminant degradability. Oxygen respiration measurements conducted routinely (e.g., quarterly) should be used as an indicator of when system shutdown should be considered. Only when respiration rates drop to background levels (i.e., those observed in uncontaminated soil of the same type) would confirmatory soil core samples be collected and analyzed for specific constituents of interest to verify contaminant removal. Leeson and Hinchee (1995) indicate that respiration rates below 1 % O_2/day represent background. If in situ respiration starts significantly above 1%/day, and then drops below this value, it is indicative of a halt to biological treatment. This halt may be due to a variety of factors, including:

- Changes in soil moisture (e.g., raised water table) occluding the pore in contaminated zone, preventing the delivery of oxygen. This can be investigated by observing changes in soil moisture and the local water table.
- Reduction in available macro or micro-nutrients, limiting biological activity. In some instances, bacterial populations "run-out" of nutrients such as phosphate necessary for respiration, even though there are adequate sources of carbon (i.e., contaminant) and oxygen. In situ addition of nutrients, or collection of soil samples for bench scale tests can elucidate these limitations.
- Reduction in available carbon (i.e., contaminant) for respiration. Rebound testing (see paragraph 9-9) can help evaluate this possibility. This result may help make the case for site closure.

9-6. System Shutdown Checklist

A system can be automatically or manually shut down to minimize hazards and aid in decontamination of equipment and areas of the project. There are several reasons for shutting down a system:

- There may be a power loss at the site.
- Equipment failure may initiate shutdown in the control systems.
- The control systems may identify an operating condition that warrants shutdown.
- A system may be shut down for maintenance.
- Evaluating remedial progress by performing rebound tests.
- Remediation may be complete.

a. Emergency shutdown. If the system is automatically shut down, an operator should be called to check the system. Depending on the configuration of the system, there are several observations and notes an operator should make. If a control system includes a FIRST OUT indication (an indicator panel with lights to identify the failure), the operator is informed of the reason for the shutdown; however, it is expensive to include FIRST OUT indication for all possible influences on a system. If failure identifications are not included, the operator should check the unit for broken equipment, piping, hoses, or ducts. Accumulated liquids should be checked and stored properly. Check for electrical power failure. If there are no apparent failures or reasons for shutdown, the system can be restarted and the operator can watch or even listen for causes of a failure.

b. Maintenance shutdown. If the process system is intentionally shut down, there are subsystems that should be checked. Decontamination of the system can lessen exposure problems during maintenance and dismantling of equipment. Steps include:

- Remove liquids from collection points.
- Isolate extraction well(s) and draw clean air through the entire system.
- Shut down vacuum pump(s) or extraction blower(s).

- Close isolation valves.
- Disconnect electrical power to equipment.
- Log the event.

Depending on the reason(s) for shutting down the system, decontamination procedures could be more stringent.

c. If the operator believes that the site is approaching "clean" or if there is interest in trying to understand and quantify the extent of rate-limited mass transfer (e.g., diffusion from low permeability strata), then a rebound test may be performed. Shutdown for rebound tests should proceed according to the shutdown procedures described in the site specific O&M manual. However, prior to shutdown for rebound testing, it is important to collect a complete set of system performance data. This data should include:

- Flow rate and concentration(s) from each extraction well and vacuum applied to each well (for SVE systems)
- Injection rates to each injection well (if applicable).
- Soil gas concentrations of site specific VOCs, gaseous O_2, CO_2, and methane from both monitoring points and extraction wells.
- Vacuum/pressure distribution within the treatment area, e.g., vacuum measurements at vadose zone monitoring points and nearby water table wells.
- Groundwater elevations (if the contaminated zone is near or within the capillary fringe) in the treatment zone, including degree of upwelling at extraction points.

The extracted gas concentrations and flow rates may have to collected multiple times if a model is used to quantify diffusion limited mass transfer (see paragraph 9-9). Groundwater and soil VOC concentrations are not particularly useful to evaluate rebound.

d. Remediation shutdown. In the later phases of remediation, extraction wells may be shut down one at a time. A wellhead valve can be included to isolate each well when cleanup criteria are met. The system should be designed to operate at reduced airflow rates without jeopardizing the performance of the system. Final shutdown of the system should follow the same activities as those for maintenance shutdown. Decontamination procedures should be followed to minimize loss of contaminated materials to surrounding areas.

9-7. Closure Report

Once remediation has been completed, a closure report/construction documentation report should be prepared to verify and document the activities and results of the remediation project. It should be noted that prior to the preparation of the closure report, the design team must determine if the acting regulatory agency has a specific format to follow and/or additional forms to be filled out.

9-8. Long-Term Monitoring Requirements

Long-term monitoring requirements following system shutdown, if any, will be defined in the SAP and perhaps modified pursuant to data collected during the operation of the system. Typically, analyses will be for selected target compounds rather than the full suite of site compounds. Care must be taken to collect and analyze the samples consistently with the collection and analysis procedures used during prior phases of the project to maximize comparability. The SAP should include provisions for resampling should an unusual positive result be found during this stage. The data should continue to be entered into the database if one had been implemented.

9-9. Rebound

As previously described, the rate of contaminant removal by soil venting is generally fast during early phases of operation and then becomes progressively slower until it approaches a relatively low value. When a soil venting system is turned off and then on again, there is generally a spike in the rate of contaminant removal, as depicted in Figure 9-2. This phenomenon is usually described as ***rebound***, that is the concentrations of the contaminants rebound toward their initial higher levels after soil venting has ceased for some period. Rebound of vapor concentrations implies that rate-limited mass transfer is occurring during soil venting. For example, if air extraction rates exceed the rate of diffusive mass transfer from within the pore water to the air-water interface and then into the flowing air stream, contaminant concentrations in the extracted air can diminish without removing all of the contaminant from the pore water. When extraction stops, the diffusion process continues and eventually the concentration(s) within the soil pores that are most conductive to air begin to rise. If a soil gas sample is collected or extraction begins again, then the contaminant concentrations will have "rebounded". Rebound will be observed whenever air extraction occurs faster than the rate of contaminant diffusion from some sequestered location. Contaminants can be considered sequestered if they reside outside of the air-filled pores that conduct the majority of the air that flows to the extraction well.

a. What is the significance of rebound? At many sites, the objective of soil venting is to reduce soil contaminant concentrations to below a specific value. Those portions of the subsurface that can readily be swept by air that flows due to soil venting may reach these target values. However, if concentrations are observed to rebound, then there is most likely soil where contaminant concentrations have not been appreciably reduced to target clean-up levels. Thus, even at sites where substantial contaminant mass is removed by soil venting, this "sequestered" contamination can often cause the site to fail to meet cleanup objectives.

b. How is rebound measured and assessed? Rebound in the simplest sense is observed when a system is shut down for a time, and then vapor phase concentrations are observed to rise in the treatment area. This phenomenon is observed at most sites, however, site specific conditions such as soil stratigraphy, moisture content, and historical pattern of contamination cause the rate at which contaminant concentrations rebound to vary dramatically from site to site. There is rarely a systematic approach applied for measuring rebound or for evaluating the rate and extent of concentration rebound. Instead, rebound tests are often used to qualitatively evaluate the progress of remediation, or sometimes quantitatively to compare the rebounded concentration at some designated time to a specified "standard". However, a properly executed rebound test can provide much greater insight into the status of remediation. Appendix F provides a detailed approach for performing rebound tests and for interpreting the data collected before and during the test. In addition, Appendix F provides the mathematical framework that is the basis of rebound data evaluation, as well as the basis for modeling SVE/BV cleanup rates and predicting remediation endpoints and timeframes.

c. Estimating the Impact of Diffusion Limitations on Remediation Timeframes

(1) By measuring rebound rates and using a simple analytical model (Brusseau 1996) some practitioners are able to estimate the impact of rate-limited mass transport on remediation timeframes. Praxis Environmental Technologies, Inc. developer of the Pneulog™ tool, reports that mass transfer constraints, order-of-magnitude total mass, and time to cleanup can be estimated from historical concentration data and rebound test data. Figure 9-2 shows data collected using a Pneulog™ device to vertically profile extracted concentrations and flow rates in a single SVE well during a rebound test. SVE was performed at this site for 12 days, then paused for four days, and then reinitiated at the same flow rates as before. The data show the characteristic rebound in extracted vapor concentrations that is seen in most SVE systems. At this site, the rebound in TCE concentration is presumably due to diffusion from a less permeable zone into the pathways that transmit most of the air to the extraction well. After the pause, a rebound in the extracted vapor concentration of almost 10 percent was observed.

(2) Figure 9-2 also includes a plot of the results of Brusseau's model, with best-fit parameters, and displays a close match with the measured concentration decay and rebound. The model has been developed in the academic literature (Brusseau 1996) but is used infrequently in field practice because the proper data are not collected or practitioners are not familiar with the model.

The basic simplifying assumptions in the model are:

- soils are categorized as two-domain, i.e., permeable to air flow (mobile) or not (immobile); and
- the early flushing rate of the mobile zone by clean air is rapid enough to justify averaging the contaminant concentration in the mobile zone.

(3) Typical SVE flow rates flush the mobile zone with clean air every few days justifying the averaging assumption. Most sites readily meet the conceptual model of mobile and immobile zones for air movement during SVE. A third category of low flow zones (e.g., silts) can be added if sufficient site data exist. Air moves through the mobile soils and contaminants must diffuse out of immobile zones before being extracted. The form of the equation describing the vapor concentration in the mobile zone (assumed equal to the extracted concentration) is roughly:

C_{mobile} is a function of [Contribution of Mobile Zone] + [Contribution of Immobile Zone]

or

$$C_{mobile} = f(\Theta_1 e^{r_1 t} + \Theta_2 e^{r_2 t}) \tag{9-1}$$

where:

$\Theta_1 =$ an advective decay constant

$\Theta_2 =$ a diffusive decay constant

$r_1 =$ a function of air residence time within the soil pores

$r_2 =$ a function of the compound's diffusivity in the rate-limiting soil type

$t =$ elapsed soil venting time

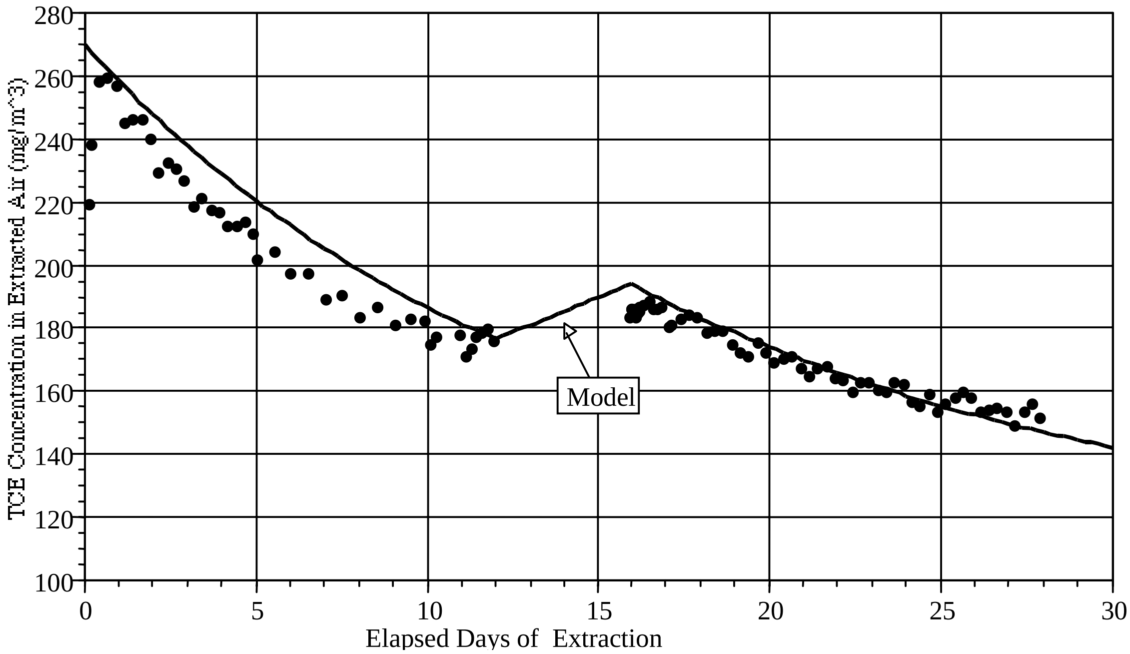

Figure 9-2. Measured and Modeled Extracted TCE Concentrations during SVE (Figure Provided Courtesy of Praxis Environmental Technologies, Inc. Burlingame, CA)

(a) The first exponential term is dominated by the timescale associated with the total volume of contaminated soil and the air extraction rate. This is a convective process. The second term is dominated by diffusion from the immobile zone into the mobile zone. For the rebound test, when extraction is zero, the magnitude of r_1 becomes equivalent to that of r_2 because all processes are then diffusion dominated. Therefore, the rebound concentration yields an estimate for the diffusion rate. Additional exponential terms can be added if other sources can be quantified (e.g., off-gassing from contaminated groundwater or evaporation of a NAPL) or if low flow zones such as silts make significant contributions. As SVE progresses at a site, the model coefficients can easily be revised. The immobile fraction of the soil becomes the dominant parameter in reaching cleanup and the longer SVE operates the more accurate this parameter estimate becomes. In the past, sites were often described solely by the convective exponential term and ignored a determination of the longer transient associated with the diffusive exponential term. Neglecting the contribution of the immobile zone resulted in vastly underestimating the time to reach a specified cleanup goal and the total mass of contaminant at the site.

(b) Fitting the multi-region model to the extracted concentration will also allow mass estimates to be calculated. The cumulative mass removed will be determined by integrating the extracted concentration represented by equation (7-1) over time from zero to the present time and multiplying by the extraction rate:

$$\text{Mass Removed} = \int_{t'=0}^{t} Q(t')C_{mobile}(t')dt' \qquad (9\text{-}2)$$

where

Q = the air extraction rate (L^3/T)

t' = elapsed SVE time

C_{mobile} = extracted concentration

The extraction rate Q is usually constant over specified periods making the integration straightforward. An order-of-magnitude estimate for the total initial mass will be obtained by letting the integration extend to infinity.